Numerical Simulation of Train Aerodynamics

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Abstract

Geographical limitations have always been a major concern in Singapore. As demand for a more efficient transport system to accommodate the rising population increases, alternatives such as underground spaces have been explored and made available The most recent example is the newly introduced Downtown Line, and many developing transport lines have also exploited the spaces Singapore can offer underground. With the transport lines built underground, the trains are expected to operate in confined spaces over a long period of time. The objective of this project is to study the aerodynamic behavior of the airflow around the train as it travels through the tunnel. Simulations of several positions of the train with respect to the tunnel were performed with Computational Fluid Dynamic (CFD). These numerical predictions are conducted using a commercial CFD code ANSYS Fluent. The results achieved show the presence of huge fluctuation in the pressure over the train. The pressure distribution at different train positions relative to the tunnel can also be observed. The exposure to constant pressure variation can sometimes have an impact on the structural integrity of the train. If high-speed trains were to be used in the future, these pressure variations would have a profound, if not catastrophic impact on the trains if they are not designed adequately. Besides the external train structure, proper sealing of the train doors is equally important. In an event of air leakage, passengers will feel discomfort due to the high differential in pressure.

1 INTRODUCTION

With an area of 680 square kilometres, geographical landscape limitations have been a major issue in Singapore. [1] In order to have sufficient land for industries, infrastructures, water catchments and military needs, underground spaces have been put into good use. One good example is the construction of the new transport system underground. Approximately 80 kilometers of Singapore Mass Rapid Transport (SMRT) lines are already underground [2]. And this number is expected to continue growing with more train lines implemented in the future.

With the uprising needs of the underground spaces, it is important to optimize the underground usages. The design of the tunnels then became a critical aspect; this hinges on a few elements:

i) the structural integrity (to withstand the vibrational and transfer of loads especially in close proximity to infrastructures)

ii) The construction cost and efficiency (optimizing the underground spaces to allow the train to operate at the optimal efficiency).

The train aerodynamics plays an influential role in determining the design of the tunnel (tunnel cross section, pressure relief shafts etc. [3]. With the new transport systems underground, the trains will be operating in long tunnels over a long period of time. Hence, the pressure variations within the tunnel will directly influence the passenger comfort in the train.

Due to space confinement, as the train is traveling through the tunnel, there is an increase in air movement and augmented velocities in front of and at the rear of the moving train. [4, 6] Air confined within the tunnel walls propagate into pressure waves; compression waves at the front of the train, expansion waves at the rear of the train. [7] The strength of the pressure waves propagation is influenced by the blockage ratio of the train in the tunnel (defined by the ratio of the train cross-section to the tunnel cross-section), the shape of the train nose and tail, the train velocity, the shape of the tunnel entrance and exit, the tunnel length and the roughness of the train body and tunnel walls. [3, 8 & 11]

This project aims to understand the behavior of the aerodynamics parameters (primarily pressure and velocity) over the train when it is outside <u>*and*</u> when in the tunnel.

The project will, therefore, be divided into seven areas:

1. The train moving external (there will be no tunnel)
2. The train approaching the tunnel entrance
3. The train just entering the tunnel
4. Half of the train has entered the tunnel
5. The train passing through the tunnel
6. The train about to exit the tunnel
7. The train is leaving the tunnel (halfway out of the tunnel)

The train will be positioned statically at different locations of the tunnel in each area of study.

2 METHODOLOGY

2.1 Geometry Model

The SMRT Circle Line train is selected for this work, with the geometry of the train modeled in Solidworks 2014 (Figure 1a) in full-scale dimensions. However, due to the confidentiality issues, the fine details of the train and the tunnel (train door, gearbox assembly and wheels at the bottom of the train and train tracks etc.) are not available and hence neglected at the current stage of the study. A simple tunnel design of length 50m was used instead (Figure 1b). The blockage ratio (train cross section to tunnel cross section) was assumed to be approximately 36.88%.

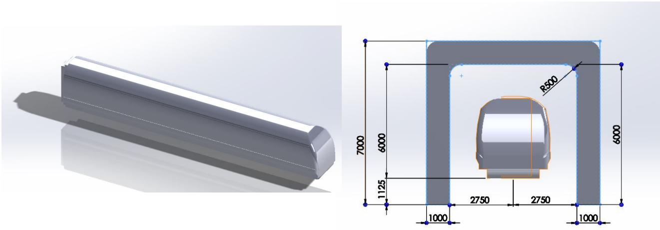

Figure 1(a) Geometry model of the train. (b) Cross section of the tunnel.

2.2 Computational Domain

To accommodate the geometry model and ensure sufficient results can be captured, a computational domain of dimensions $90.6m \times 10m \times 16.125m$ was implemented (Figure 2). The computational domain consists of six boundaries: two different inlets (Pressure inlet and Velocity inlet), three outlets (Pressure outlets) and one wall surface.

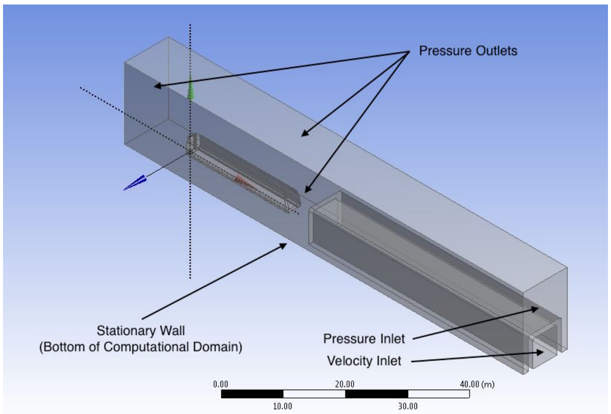

Figure 2 Computational Domain Boundaries

A hybrid unstructured computational mesh was generated using ANSYS Meshing (Figure 3). Inflation layers were implemented on the train surfaces to capture the boundary layer region accurately. The results in the boundary layer region will provide a good appreciation of the viscous forces on the train and the transition of laminar to turbulent flow along the train body.

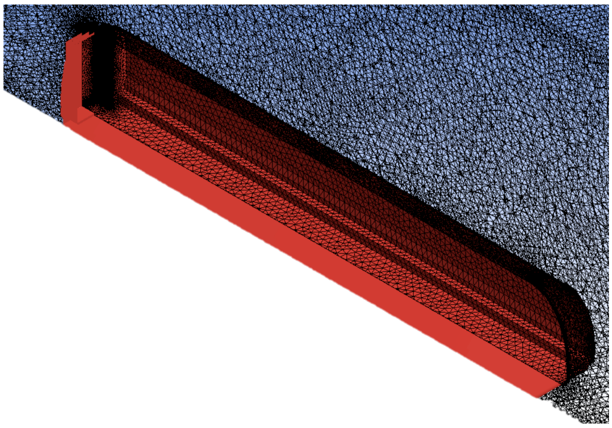

Figure 3 Hybrid Unstructured Computational Mesh

2.3 Boundary Conditions and Other Computational Settings

Commercial Computational Fluid Dynamics (CFD) software, ANSYS Fluent, is used to solve the steady Navier-Stoke's equations. The standard k-epsilon turbulence model with standard wall function was utilized. This turbulence model is known to be useful for flows with relatively gentle pressure gradient, and it includes two transport equations to represent the turbulent properties of the flow. [12]

The train will be simulated to travel at a velocity of 38.9 m/s (140km/h). Furthermore, for a more realistic simulation, a gauge pressure of 5 Pa is introduced through the second inlet. This is to replicate the scenario in which windy conditions are present and the air around the tunnel is moving at a velocity of 3m/s.

3 Results and Analysis

In the experiments done by Gilbert et al. [13], a train of model-scale length 4.24m was used to traveling through an 8m long tunnel at a velocity of 32m/s. The velocities in the tunnel were measured by a Cobra probe PRB1, positioned at a distance of 4.88m from the inlet. The blockage ratio was 30%. Comparing the experimental data from Gilbert et al. [13], the results from the numerical simulations showed similar trends in the variation of the velocity as the train is traveling through the tunnel. However, the numerical simulations showed a much higher increment in velocity as compared to the experimental data. This deviation can be due to several reasons:

- High fluctuations in measured velocities during the 25 experimental runs due to the limitation of the Cobra probe. The Cobra probe registers only mainstream flow but not complex reverse flow.
- The difference in increment in velocity can be due to the applied no-slip condition for the tunnel wall and the train in the numerical simulations

Since the experimental data and numerical simulations came to an acceptable agreement, the results achieved in the numerical simulations can be further analyzed.

The project was divided into different area of study for simulations.

Case 1	The train is moving (no tunnel)
Case 2	The train is approaching the tunnel entrance
Case 3	The train just enters the tunnel entrance
Case 4	Half of the train has entered the tunnel
Case 5	The train is passing through the tunnel
Case 6	The train is about to exit the tunnel
Case 7	The train is leaving the tunnel (halfway out of the tunnel)

The number will be used to represent each area of study in the discussion.

3.1 Contours around the Train Body

The behavior of the aerodynamic parameters (pressure, velocity) around the train body will be studied in both vertical and horizontal plane located at the middle of the train. The direction of travel in these contour plots will be from right to left.

3.1.1 Velocity

The contour plots of the velocity of the airflow around the train as it travels through the tunnel are shown (Figures 4 and 5). The velocity ranges from 0 m/s to approximately 100 m/s. Turbulent flow can be observed at the end of the train body for Case 2-5. This turbulent flow can be due to the geometry of the train nose, the flexible connector located at the rear of the train and also the induced wind factor from the surrounding. In Case 6-7, as the train exited the tunnel, the flows in both vertical and horizontal planes were observed to join back at the rear of the tunnel in a very laminar manner. These analyses were complemented with the contour plots of the turbulence kinetic energy around the train body (Figure 6 and 7).

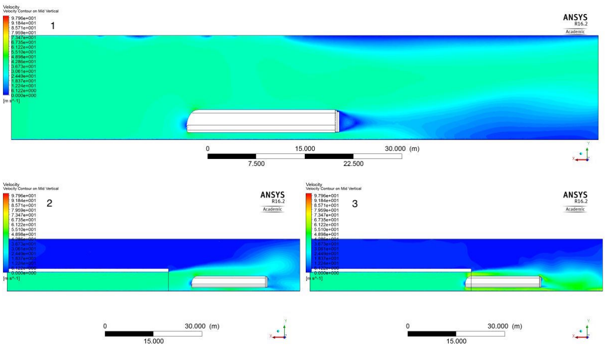

Figure 4(a) Velocity Contours Around the Train in Vertical Plane for Cases 1-3

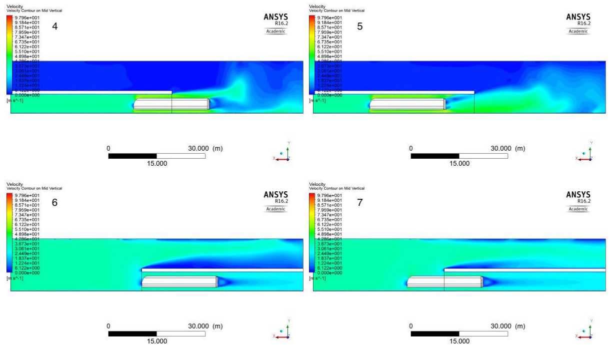

Figure 4(b) Velocity Contours Around the Train in Vertical Plane for Cases 4-7

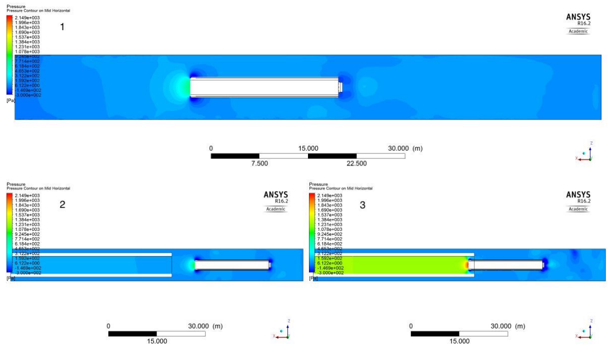

Figure 5(a) Velocity Contours Around the Train in Horizontal Plane for Cases 1-3

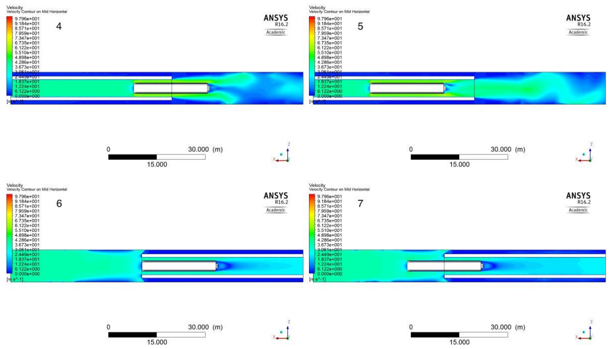

Figure 5(b) Velocity Contours Around the Train in Horizontal Plane for Cases 4-7

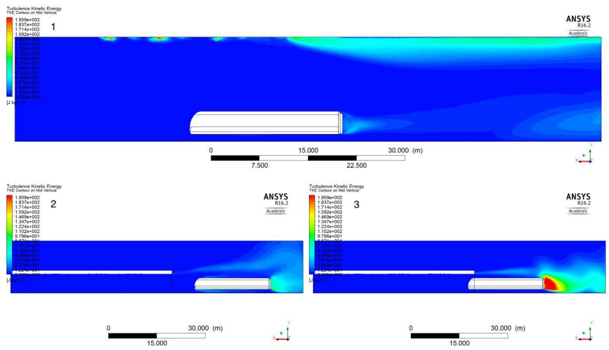

Figure 6(a) Turbulence Kinetic Energy Contours Around the Train in Vertical Plane for Cases 1-3

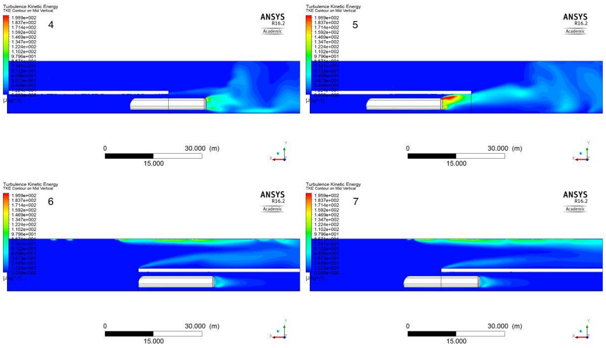

Figure 6(b) Turbulence Kinetic Energy Contours Around the Train in Vertical Plane for Cases 4-7

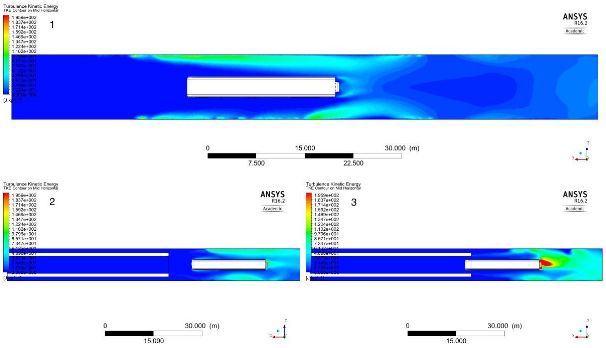

Figure 7(a) Turbulence Kinetic Energy Contours Around the Train in Horizontal Plane for Cases 1-3

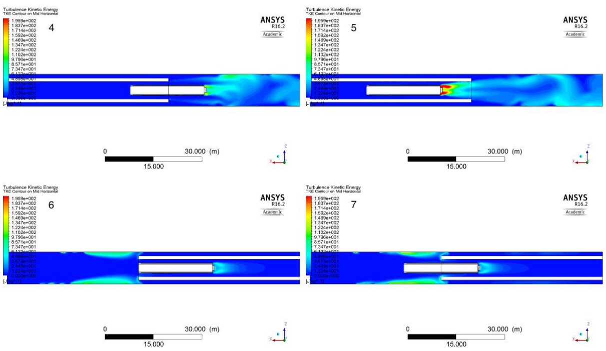

Figure 7(b) Turbulence Kinetic Energy Contours Around the Train in Horizontal Plane for Cases 4-7

3.1.2 Pressure

Figure 8 and 9 depict the contour plots of the pressure acting around the train in these different cases. The gauge pressure in the tunnel increased sharply from 86.38 Pa to 1232.46 Pa when the train enters the tunnel. This is due to the generation of the compression waves within the tunnel wall. As the train travels through the tunnel, expansion waves were generated at the tail of the train when it reaches the tunnel entrance. This was proven when the gauge pressure of the tunnel in front of the train falls to 843.06 Pa. Upon exiting the tunnel, the expansion waves greatly reduced the pressure at the train nose to 432.06 Pa.

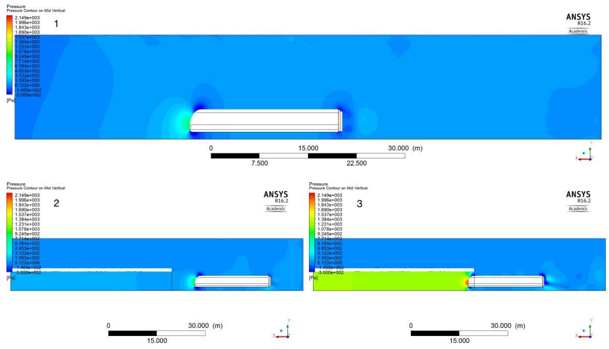

Figure 8(a) Pressure Contours Around the Train in Vertical Plane for Cases 1-3

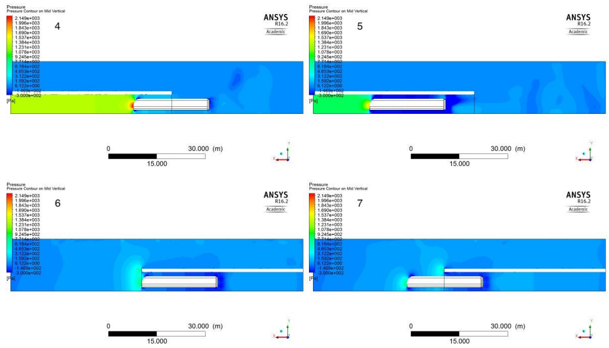

Figure 8(b) Pressure Contours Around the Train in Vertical Plane for Cases 4-7

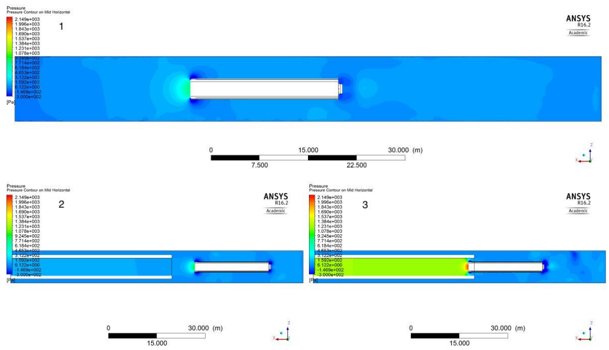

Figure 9(a) Pressure Contours Around the Train in Horizontal Plane for Cases 1-3

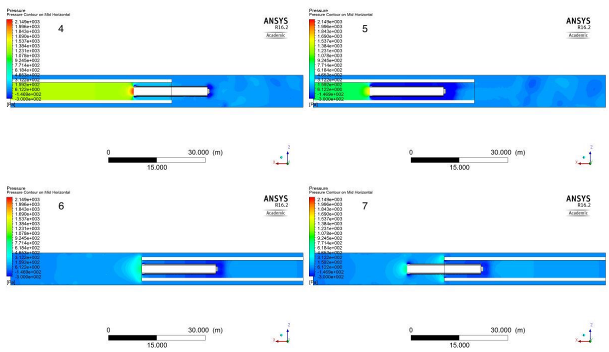

Figure 9(b) Pressure Contours Around the Train in Horizontal Plane for Cases4-7

3.2 Pressure Contours on Train Body

The illustration below depicts the contour plots of the pressure acting on the surface of the train body (Figure 10). The scale of the gauge pressure in the contour plots ranges from -2200 Pa to 2200 Pa – relative to the ambient pressure of 1atm.

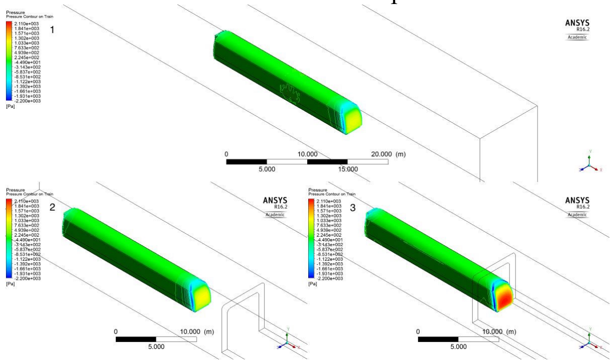

Figure 10(a) Contour Plots on the Train Body for Cases 1-3

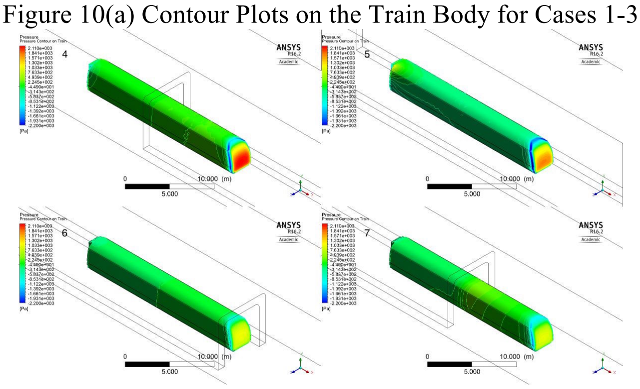

Figure 10(b) Contour Plots on the Train Body for Cases 4-7

Figure 8 shows that the pressure acting on the train body experienced very small changes as the train travels through the tunnel, whereas the nose of the train will first experience a sharp rise in pressure as the train is moving into the tunnel, then a gradual fall as it travels through the tunnel and eventually exit the tunnel. This phenomenon is because the train is traveling through a confined volume of air, thus the pressure will hence experience great appreciation and depreciation.

The pressure experienced at the train nose in each case shows that the presence of pressure waves in a confined volume can greatly affect the pressure force acting the body. The gauge pressures acting at the train nose and the train body in each case are tabulated for easy comparison (Table 1).

	Gauge Pressure (Pa)	
Case	At Train Nose	At Train Body
No Tunnel	787.30	44.45
Approaching Tunnel	931.95	12.83
Entering Tunnel	2085.85	10.05
Entering Tunnel (Midway)	2142.26	116.71
In the Tunnel	1686.95	-292.65
Exiting Tunnel	844.39	-127.08
Leaving Tunnel	796.10	225.61

Table 1 Pressure on Train Nose and Train Body

Similarly, when the train enters the tunnel, the compression waves formed will increase the pressure acting at the train nose and also on the train body. As the train moves along the tunnel, the expansion waves will then relieve the pressure on the train nose and the body. Hence the drop in gauge pressure at both locations of the train.

3.3 Pressure Variations along the Train Body

In the experiments done in Gilbert et al. [13], the Cobra probe was placed 0.02m from the side of the model-scale train with a width of 0.12m. Similar settings were applied to observe the pressure and velocity variations along the train. A line was plotted approximately 0.532m from the side of the train and the pressure and velocity variation along the line were plotted for analysis (Figure 11 and 13).

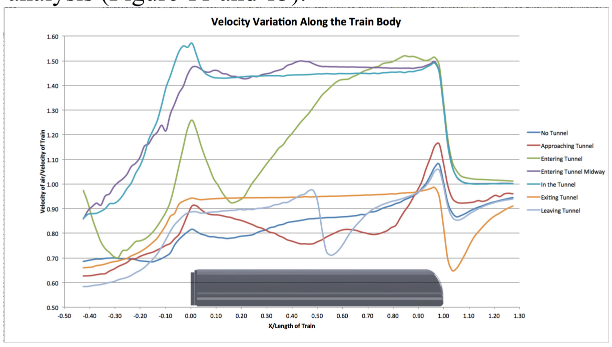

Figure 11 Velocity Variation Along the Train Body

The velocity of the air at the front of the train magnified to approximately 50% faster when the train is entering and moving in the tunnel and approximately 20% when it is approaching and leaving the tunnel. On the other hand, at the tail of the train, a decline in velocity can be observed. Similarly, the decline was significantly greater when the train is entering and moving in the tunnel as compared to the other cases. The events of velocity increments and decrements at the train nose and tail respectively were validated by the experimental data from Gilbert et al. (Figure 12) [13].

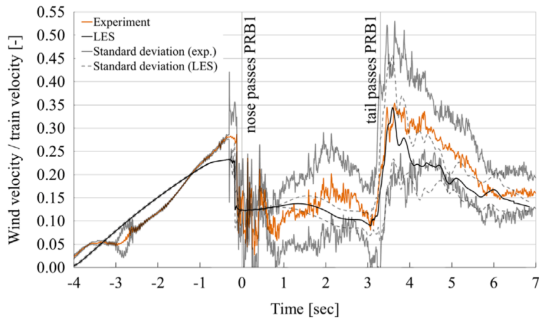

Figure 12 Experimental Data from Gilbert et al. [13]

The largest deviation in pressure was noticed when the train is entering the tunnel. This phenomenon can be due to the compression waves generated as the tunnel is moving into the confined volume of air within the tunnel. Although the pressure along the train body can be deemed to be constant, the differential pressure was the largest when the train is moving along the tunnel. It could be meant that the train will experience a 300 Pa of pressure on the train surface while moving in the tunnel. Over a long period of time, this can cause critical damage to the structure.

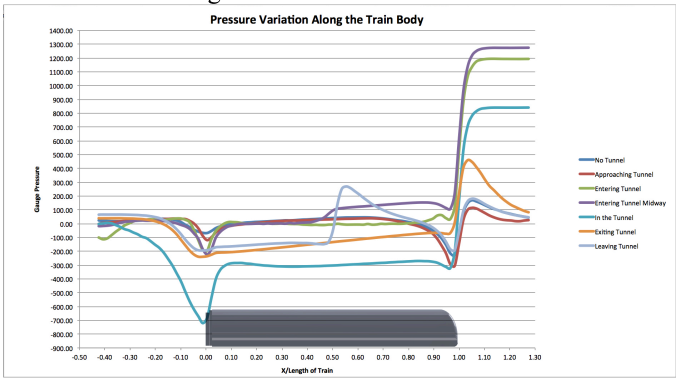

Figure 13 Pressure Variation Along the Train Body

4 Conclusion

This project analyzes the aerodynamics behavior of the airflow when the train is traveling through the tunnel by the means of solving the steady state Navier-Stoke's equations. The methodology was validated by experimental data of a reduced model-scale train running through a tunnel. The simulations were done with the train positioned at different locations with respect to the tunnel. Whilst a direct validation was not conducted (given the different operating conditions and train geometry), a similar trend in the pressure variation along the train body could be observed.

The present results gave an insight of the aerodynamic behavior in the tunnel and around the train body. From the velocity contours plotted in the vertical and horizontal plane, turbulent flow observed at the rear of the train could be due to the induced wind introduced through the second inlet and the design of the flexible connector of the train being less aerodynamically shaped. However, as the present studies only focused on the first train cabin, the effects of the turbulent flow at the rear of the train can be reduced with the presence of other cabins (increasing the length of the train).

The pressure acting on the train body and in the tunnel experienced huge fluctuations as the train moved along the train. These big deviations in pressure can be damaging to the structural integrity of the train body and create discomfort to the passenger, should there be any air leakage. This occurrence was caused by the propagation of strong pressure waves (compression and expansion waves) in the tunnel. To reduce the strength of compression and expansion waves, countermeasures can be done by adopting one or in combination [14]:

- Restriction in train speed
- Reduction in blockage ratio by increasing tunnel cross section
- Use pressure alleviation devices

The results from the simulations using CFD ANSYS had provided a good appreciation of the aerodynamic patterns around and on the train. However, the present results focused on the contour plots on the train body, vertical and horizontal planes, which are located at the middle of the train. Further work can be done to give more conclusive results, such as:

- Refine the geometry model of the train and tunnel. This includes adding wheels, gearbox assembly, additional train cabins and train track etc. into the geometry model.
- Increasing the length of the train to study the turbulence effect downstream
- The tunnel used for the numerical simulations can be changed to the actual tunnels used by SMRT lines.
- Wind tunnel testing can be done to validate the numerical results using a scaled-down model of the train and tunnel.
- Numerical runs can be done using the sliding mesh method. The computational domain will be divided into two subdomains: the stationary subdomain will consist of the tunnel, while the moving subdomain includes the moving train and a volume of air around it. This method of dynamically (instead of static conditions) modeling the train could show the pressure variations as the train moves through a tunnel.

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